Heavy Ion Direct Drive and Shock Ignition: Issues and Opportunities

L.J.Perkins[1], R.Betti[2], B.G.Logan[3], E. Lee[3], J.J.Barnard[1]

[1]*Lawrence Livermore National Laboratory*
[2]*Laboratory for Laser Energetics, University of Rochester*
[3]*Lawrence Berkeley National Laboratory*

Heavy Ion Fusion Science Virtual National laboratory

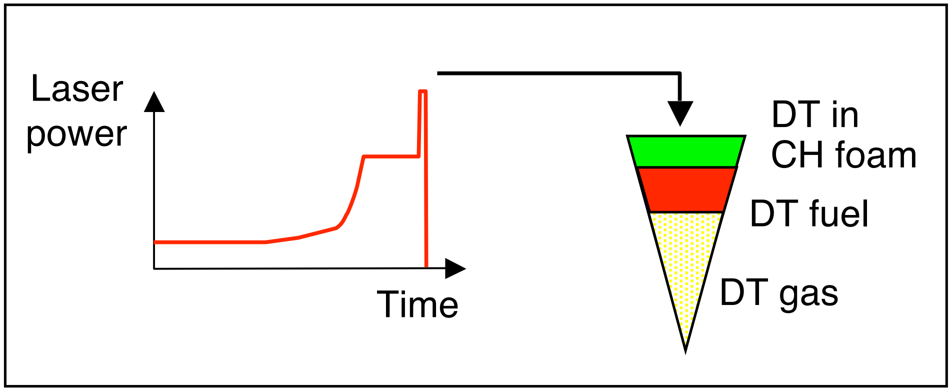
8th Program Advisory Committee Review

Lawrence Berkeley National Laboratory

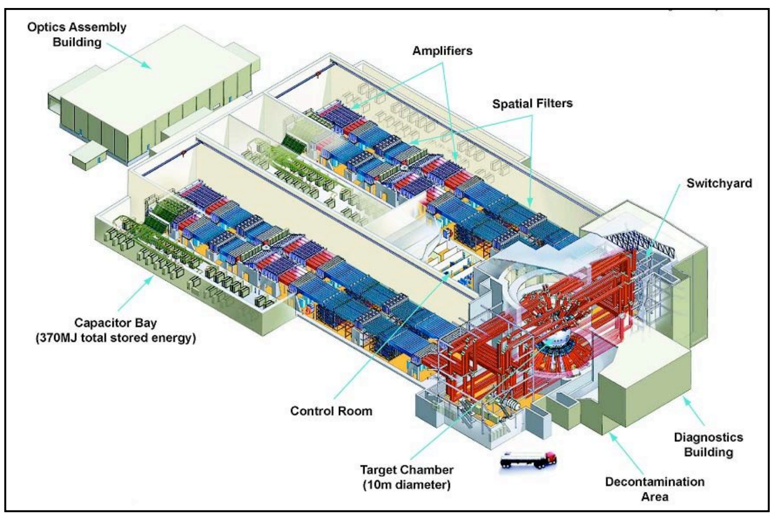
February 22, 2007

This work was performed under the auspices of the U.S. Department of Energy by University of California, Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48.

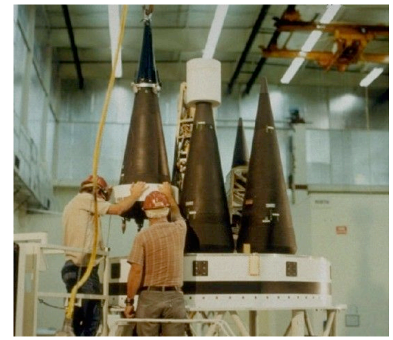
We are Studying *"Shock Ignition"* for High Gain/Yield NIF Targets: Can it be Applied to Heavy Ion Drive?



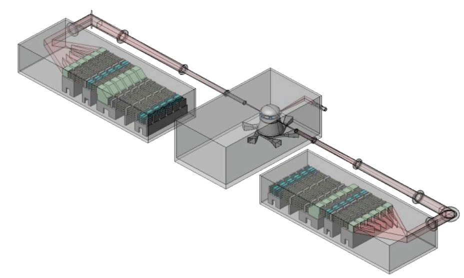
NIF (polar) direct drive campaign (≥2012)



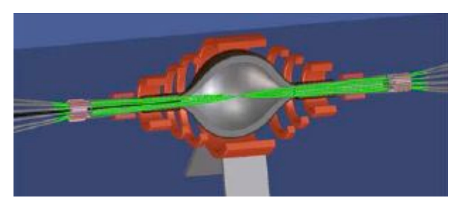
High yield targets for NNSA stockpile applications



High gain targets for laser IFE



High gain targets for heavy ion IFE?



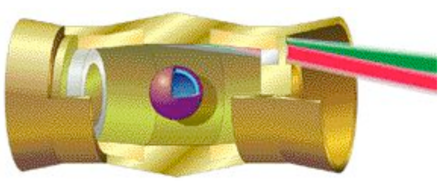
Heavy Ion Indirect-drive is Still the HIF Baseline but Presents Significant Challenges

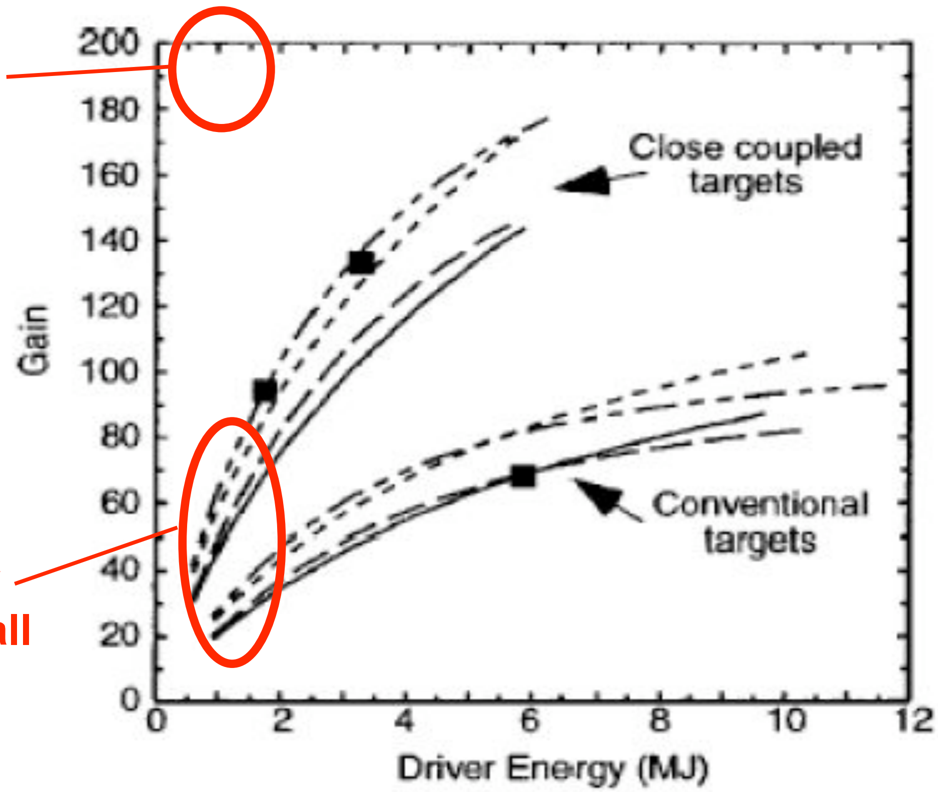
- Indirect drive has low gain; requires high drive energy with small spots
- Indirect drive presents challenges for experiments at low gain thresholds

D.Callahan - Phys Plasmas **7** (2000); HIF04 NIM

Gains of ~200@1MJ may be possible with direct drive shock ignition

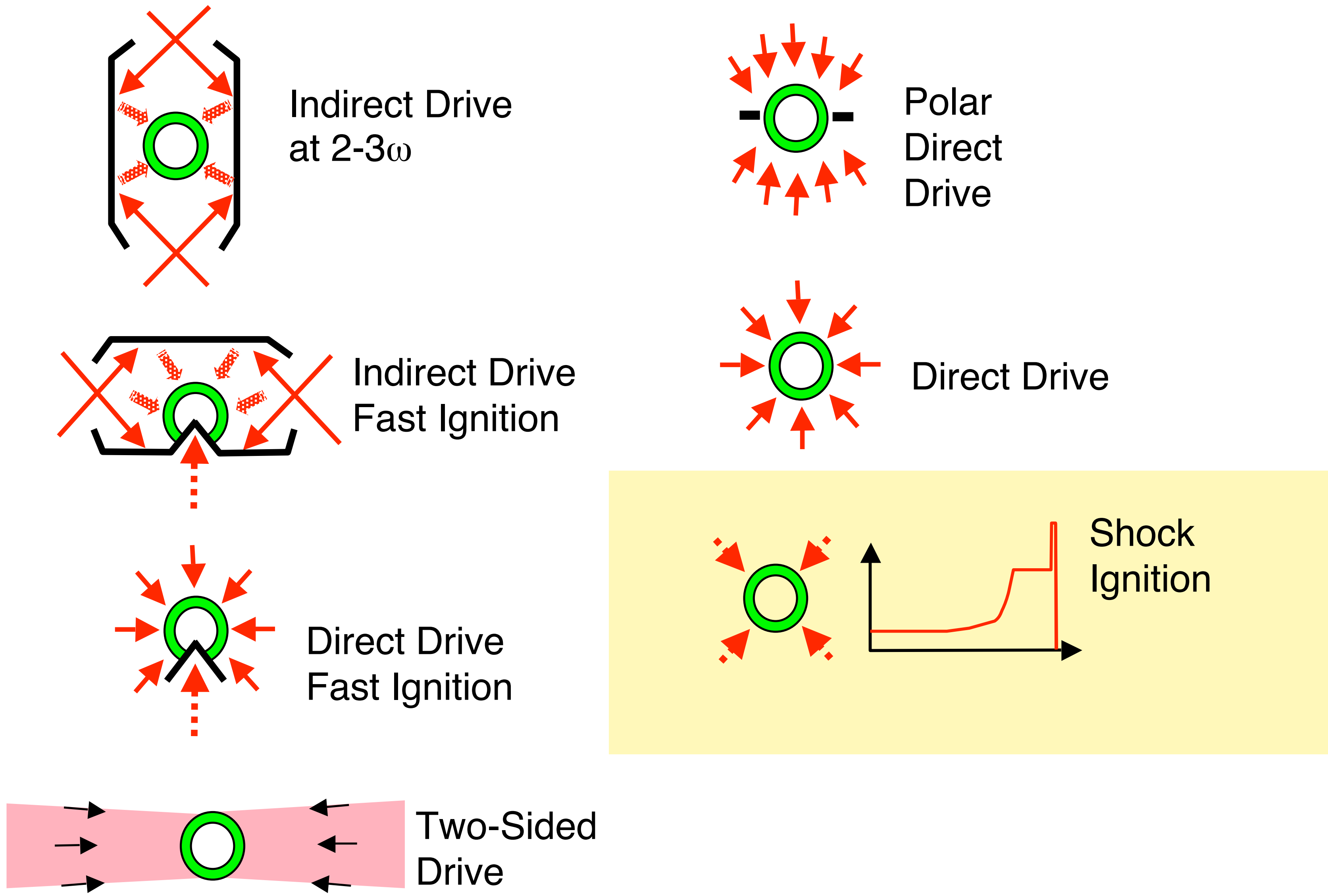
2mm capsules absorb only 1MJ out of 7MJ



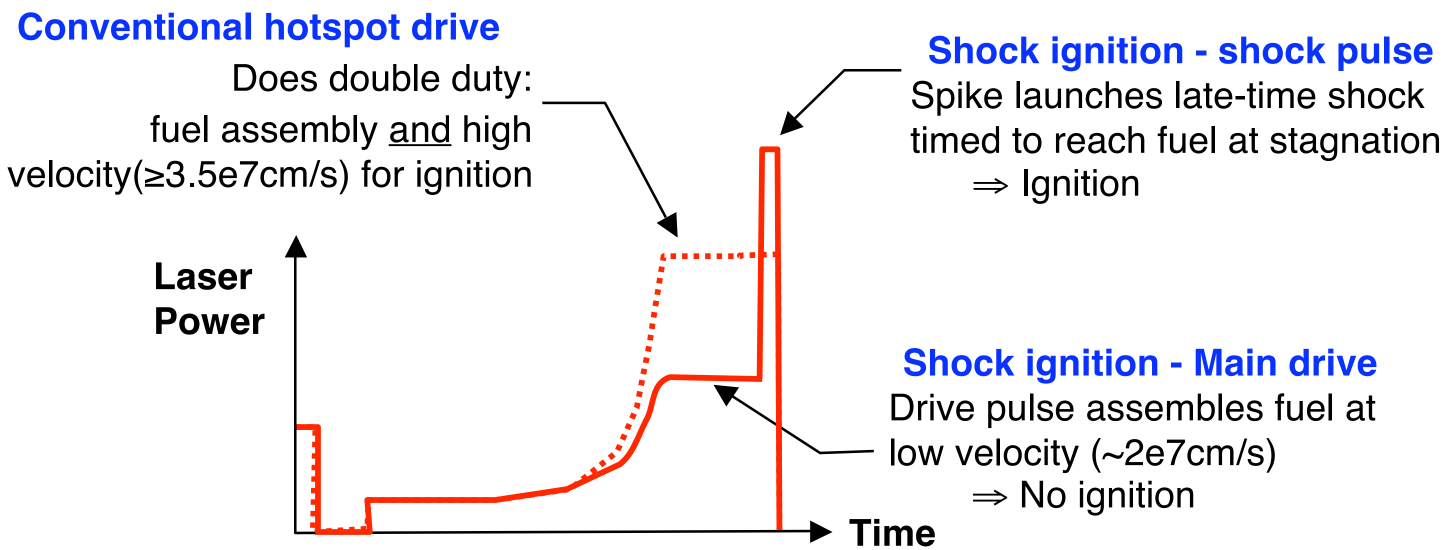


@1MJ: Gain too low and spot size too small <0.5mm

Shock Ignited Targets are A New Class of Advanced Targets under Study for Inertial Fusion Energy



Essence of Shock-Ignition*: Implode at Low Velocity and Ignite Separately



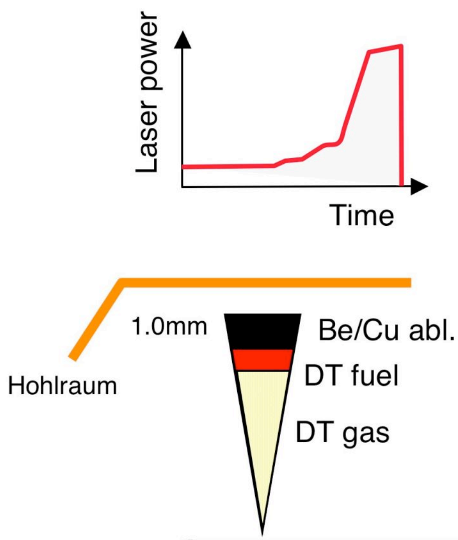
Shock-Ignition Decouples Target Compression from Ignition

- Higher target gains for the same drive energy (and vice-versa)
- Benefits similar to "fast-ignition", but: (a) time/spatial requirements probably less stringent, (b) uses same laser (no petaWatt compressor lasers req'd), (c) process modeling more tractable with today's database
- Target still relies on central ignition (like a regular hot-spot target) so conventional symmetry and stability constraints still apply
- Probably doesn't work in indirect-drive (unless PW's of shock power are applied)

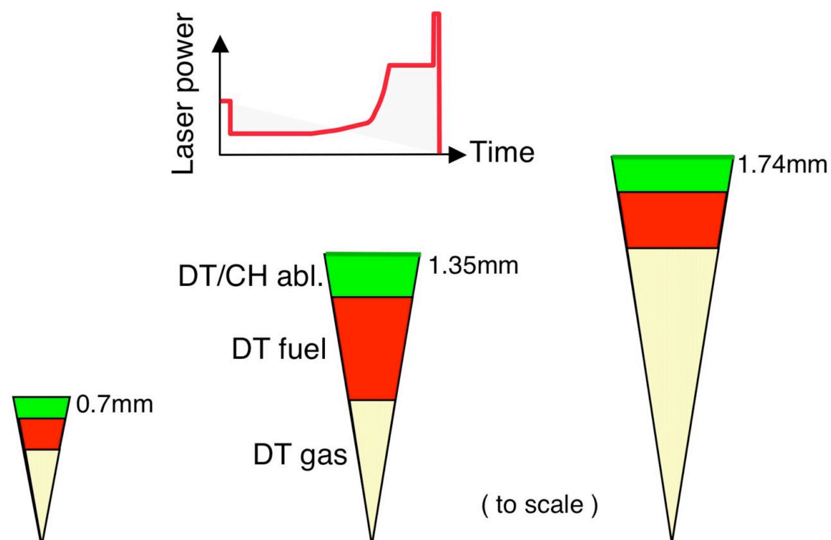
* R. Betti , C.D. Zhou , L.J Perkins, A.A. Solodov, "Shock Ignition of Thermonuclear Fuel with High Areal Density", submitted to Phys. Rev. Lett., (Feb 2007)

Initial LASNEX 1-D Results Suggest Considerable Promise for Shock-Ignited NIF Targets

NIF HOTSPOT IGNITION TARGET (~2010)



CANDIDATE NIF SHOCK IGNITION TARGETS (≥2012)

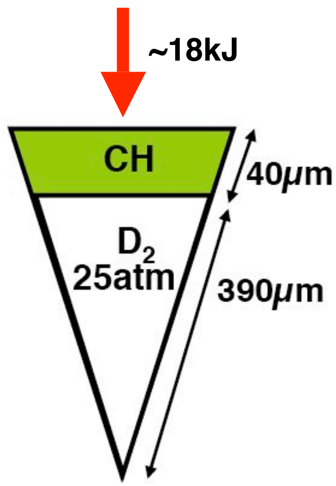


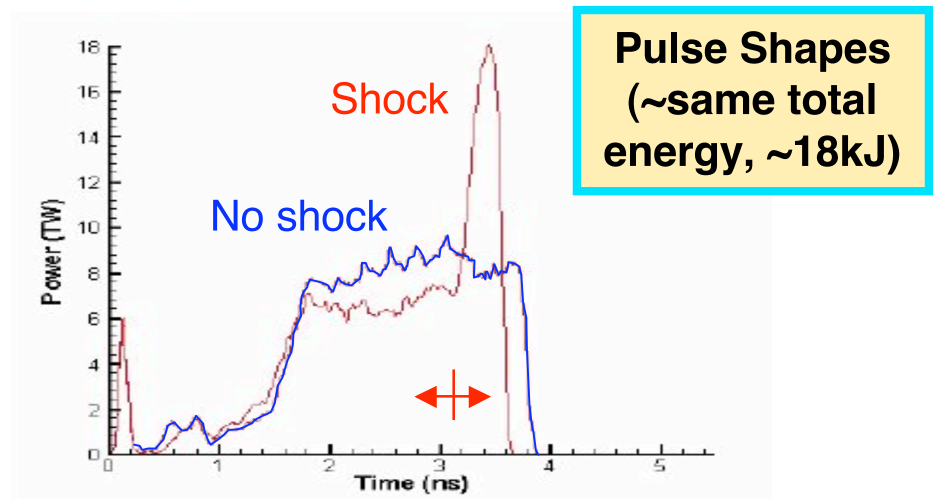
	NIF Indirect-Drive Target	Low Energy NIF Target	High Stability NIF Target	High Gain NIF / Reactor Target
Ignition Type	Hotspot	Shock	Shock	Shock
Laser Energy	1MJ	160kJ	1MJ	1.3MJ
Gain/Yield	10 / 10MJ	50 / 8MJ	100 / 100MJ	154 / 200MJ
Velocity (cm/s)	3.4e7	2.5e7	1.8e7	2.3e7
IFAR	34	35	10	33

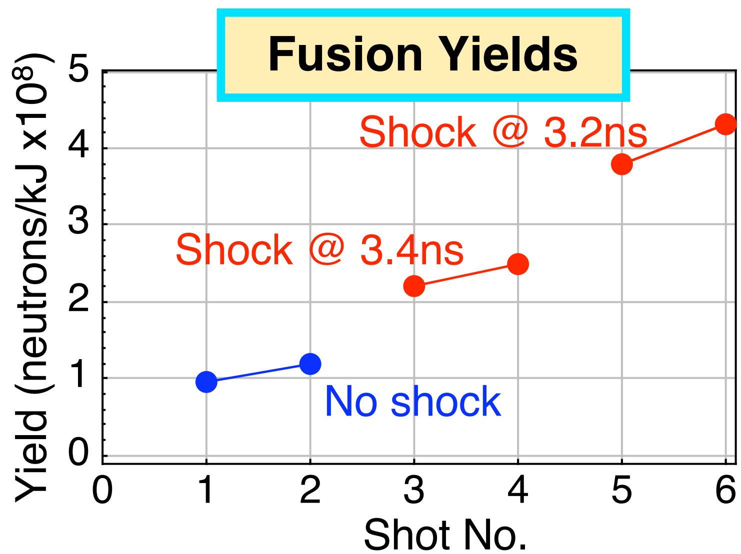
Initial Shock-Driven Experiments on Omega (Jan 2007) show Considerable Enhancements over Conventional Drive

Omega Target:

D2 gas with CH shell







ρ-R(mg/cm²)

172 – ~300

Omega record!

140 – 260

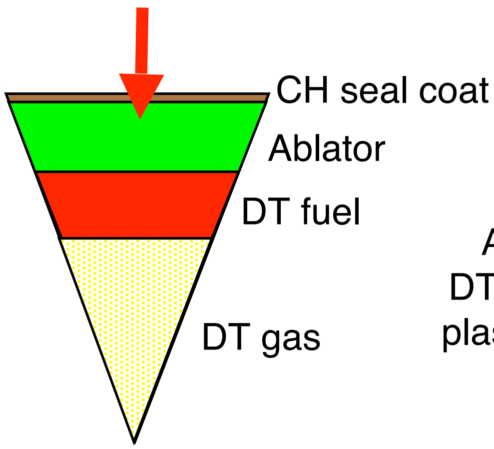
It is Time to Reconsider Direct Drive for HIF

With modern (mainly DT) direct drive capsules, super-efficient heavy-ion beam coupling and shock ignition, <1MJ drive may suffice for gains≥200 and ηG >20!

- **Shock ignition direct drive enables high gains/yields without the need for separate PW lasers**
- **Adiabat shaping and SSD beam smoothing makes direct drive viable for NIF**
- **LLE/NIF polar-direct-drive will test geometries suitable for liquid protected chambers**
- **Direct drive capsule radii >2mm allow large beam spots**
- **Neutralized drift compression allows multiple pulses of lower ion ranges**

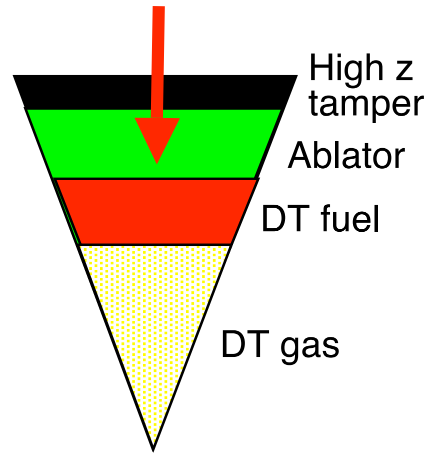
⇒ Pursuit of direct drive and shock ignition allows HIF to take advantage of ongoing progress in modern laser facilities as it had for indirect drive

Heavy Ion Direct Drive May Offer Advantages Over Lasers



Conventional Ablator

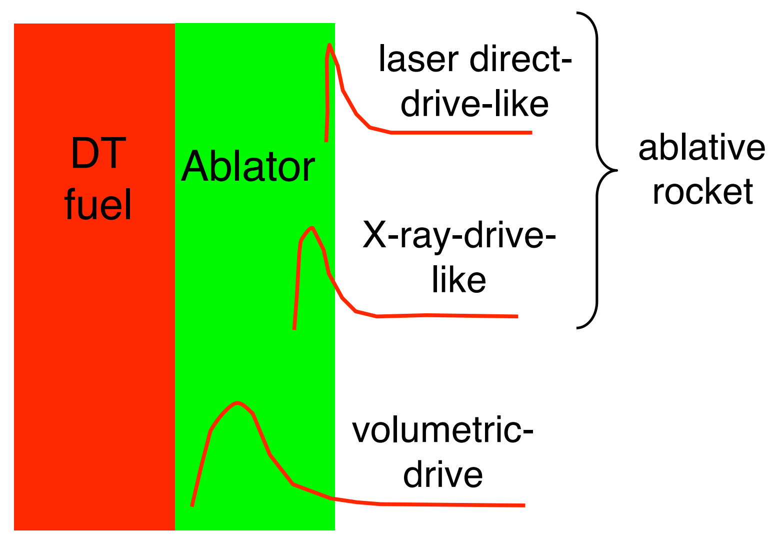
Ablator types:
DT+CH foam, CH
plastic, Be,…(+ Ta
rad block?)



Tamped "Cannon"

1-D Gains of ~50-200 May be Possible at Drive Energies of 0.5-1MJ

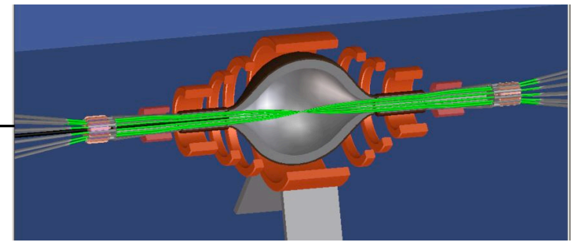
- Tailored ion ranges ($\Rightarrow m_{dot}$, P_{abl}, V_{exh})
- Higher rocket efficiencies
- Potential for tamped "cannons"
- Higher R-T ablative stabiliz., $V_{abl} \sim m_{dot}/\rho$
- Potential for dynamic focusing ("zooming") and kinetic energy control
- High driver efficiencies
- Higher rep rates

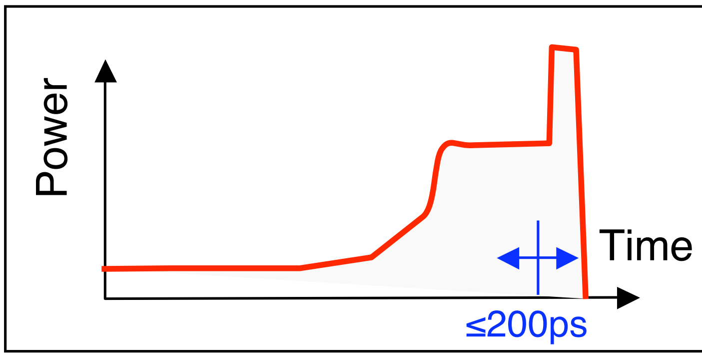


Shock Ignition with Heavy Ions: There Are Critical Issues to Address

Direct Drive is Probably Required.

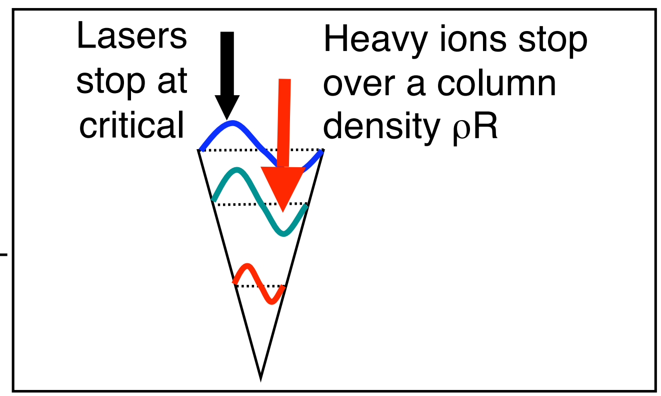
But, Two-Sided Geometry is Highly Desirable





Shock Synching will Probably Require Sub-ns Risetimes

Will Heavy Ion *Direct* Drive Exhibit Additional Instabilities Relative to Laser Drive?



Two Sided Targets Look Promising for Laser Direct Drive (But…Laser Light Undergoes Refraction)

PRL 94, 095002 (2005) PHYSICAL REVIEW LETTERS week ending 11 MARCH 2005

The Saturn Target for Polar Direct Drive on the National Ignition Facility

R. S. Craxton* and D. W. Jacobs-Perkins

Laboratory for Laser Energetics, University of Rochester, 250 East River Road, Rochester, New York 14623-1299, USA

(Received 18 November 2004; published 9 March 2005)

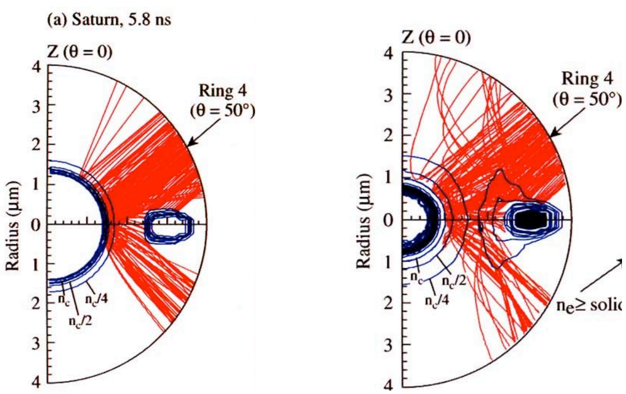
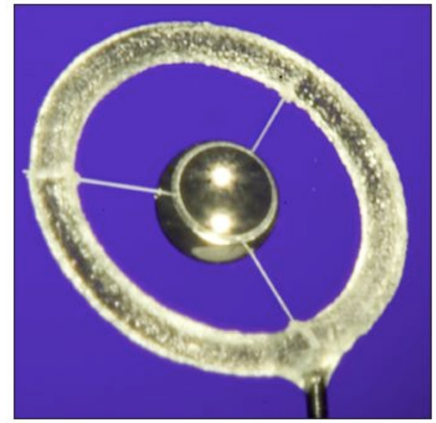
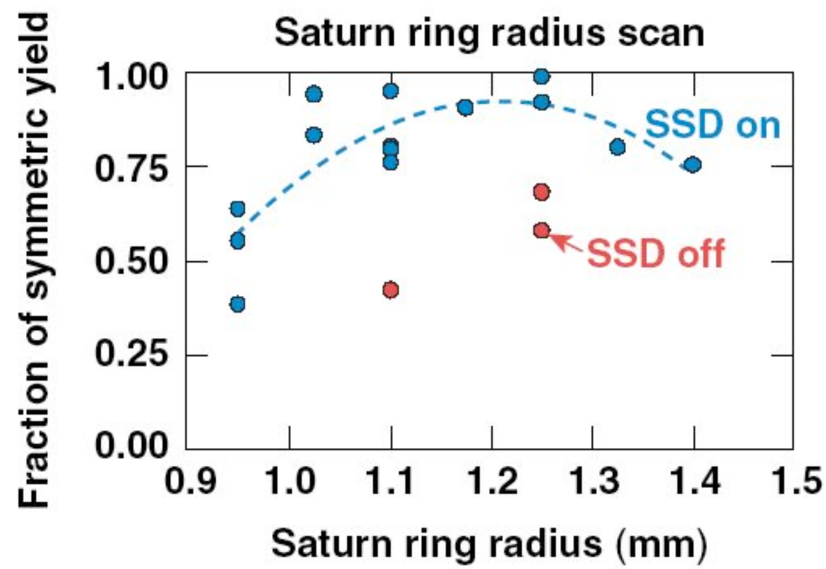


FIG. 3 (color). Electron-density contours (blue) and a representative subset of Ring-4 ray trajectories projected into the (r, z) plane (red) for a Saturn target and a standard-PDD target, at the time of shock breakout (5.8 ns) and at the end of the laser pulse (9 ns). In the Saturn design the central group of rays refract in the ring plasma at the later time (c) toward the capsule equator. The green-shaded areas at 9 ns represent material above solid density.

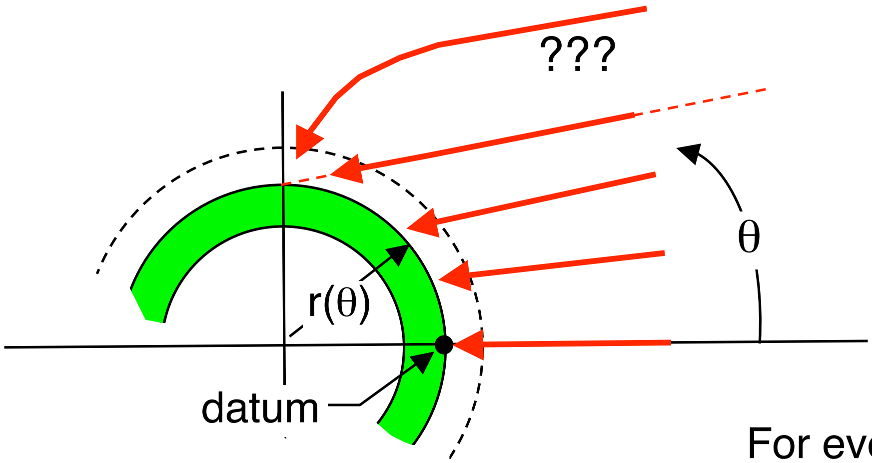
"Saturn" polar direct drive targets have been shot on Omega and have achieved ~80-90% of the full 4-Pi symmetric yield

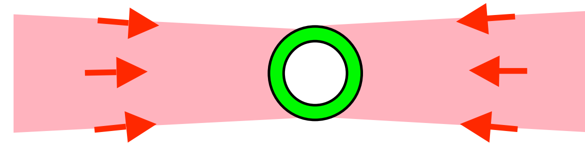




F.Marshall, *Bull APS* **51** 106 (2006)

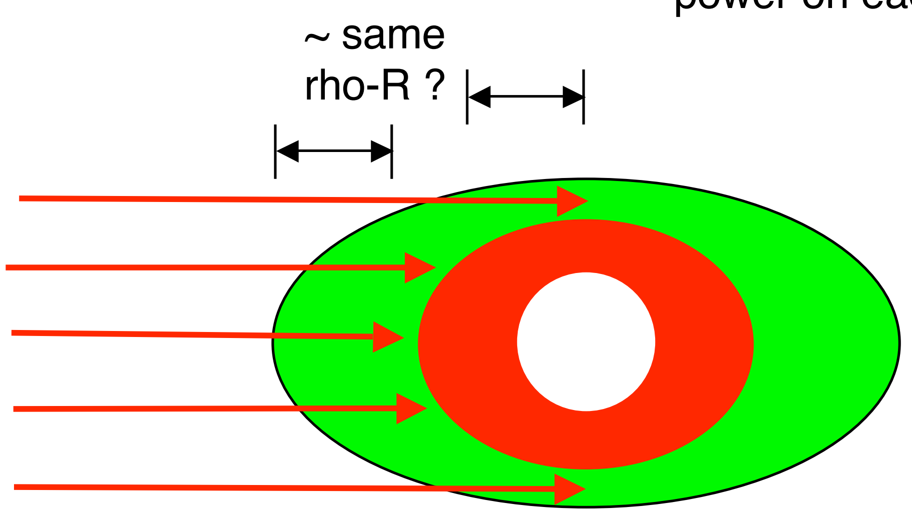
So, Without Refraction, How Do We Achieve Two-Sided Direct Drive with Heavy Ions?





For every LASNEX time step, adjust power on each ray as:

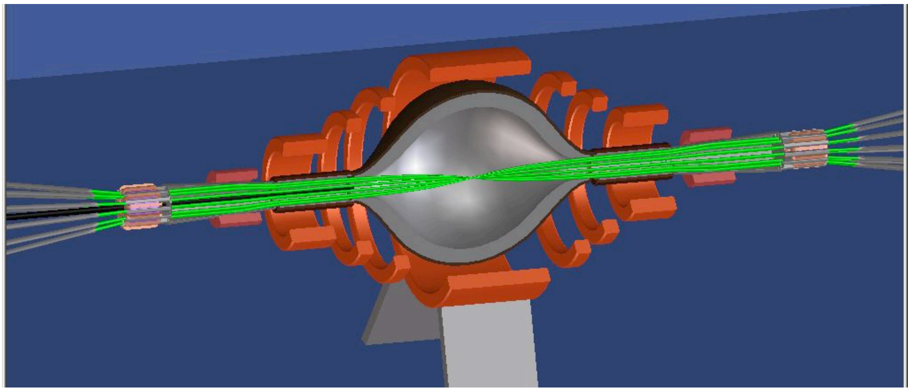
$$I(\theta) \sim \frac{I(0)}{\cos(\theta)}\left(\frac{r(\theta)}{r(0)}\right)^{3/2} f_{\mathrm{Map}}(\theta)$$



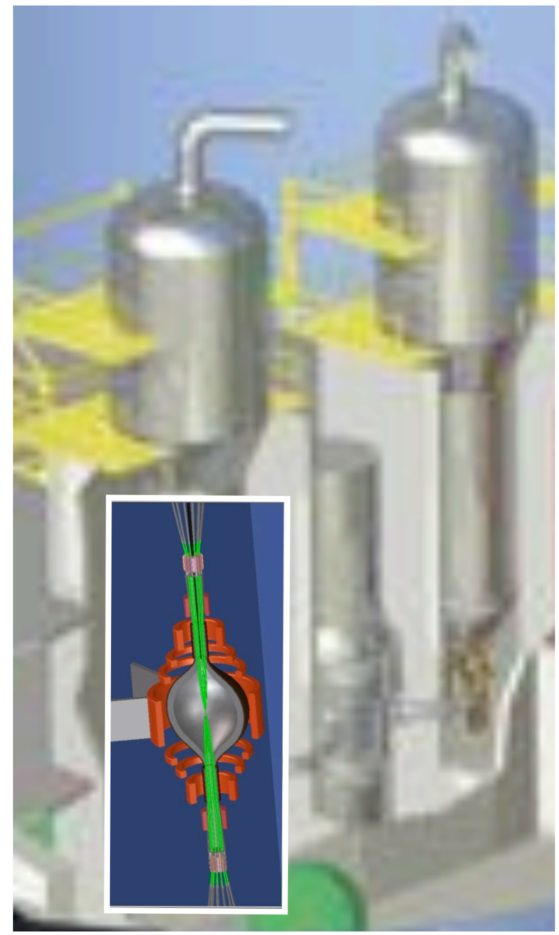
Heavy ions don't refract. But they can deposit volumetrically!

⇒ Target shimming and/or radial/temporal energy control. Is there is a solution – and can we find it?

New Concepts for Accelerators, Targets, Neutralized Transport and Chambers Offer New Vistas for HIF



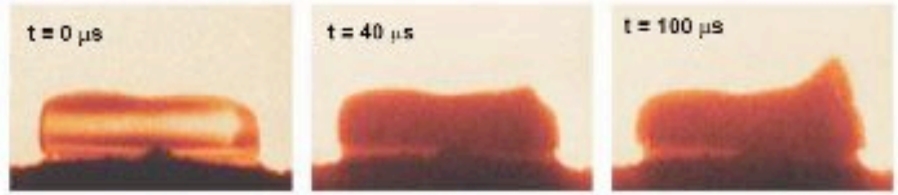
- 1MJ modular solenoid driver @20Hz
- Velocity-chirped beams, solenoid focusing
- Plasma neutralized, liquid FLIBE vortex chambers
- Shock ignited, gain 200 targets
- 200MJ yields
- 5Hz chambers x 4
- $4000MW_{fus}$, $\sim 4800MW_{th}$, $\sim 2000MW_e$



Westinghouse AP1000 (to scale)

HYDRA calculations suggest we could begin ion-driven hydro/RT studies on D2-cryo with NDCX-II (J.Barnard)

- *GSI first practiced ion-driven target hydrodynamics with cryogenic Xenon targets at beam intensities well below those required for full target ionization:*



- Direct drive hydrodynamics/RT physics can benefit from "pump-probe" <u>double pulses</u>:

Solid D_2 "payload"

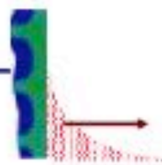
Payload and ablator D_2 layers are doped with different impurities to diagnose optical depth modulations

Time just before first pulse

Ablator D_2 layer – > than initial ion range

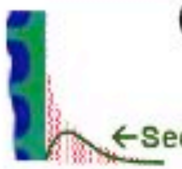
First ns ion beam pulse dE/dx (beam enters from the right)

Time ~ 10 ns later before second pulse arrives



RT "bubbles & spikes" grow measurable amplitudes.
(1) Can upstream beam GHz RF modulation reduce RT?
(2) Do RT non-uniformities in ablation plasma smooth out with time and distance (any "ablative stabilization")?

Second ion pulse arrives, and stops *<u>mostly within ablation blow-off</u>* (in 1-D approx.)!



(1) "Rocket science": what ion range/ablator thickness maximizes hydro implosion efficiency with later ion pulses re-pressurizing same ablation layer mass?

←Second ns ion beam pulse dE/dx

(2) How is RT growth affected (any "cloudy day" effect?)

With laser direct drive, later pulse ablates at fresh critical density layer further left

With laser direct drive, ablation plasma << critical density,
→Later laser light transmits through ablation plasma.
→Absorption in inverse bremsstrahlung layer moves left as ablator layer erodes

← Unique physics with ion drive using NDCX-II.
→Requires very small prepulses!